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A Comparison of Manual Scaled and Predicted foE and foF1 Critical Frequencies

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The CCIR and Titheridge foE critical frequency prediction routines were tested by comparison with 1875 manually scaled values. The foF1 critical frequency prediction routine of Millman et al was tested by comparison with 1005 manually scaled values. Plots and statistics of the comparisons are presented and discussed. From the results recommendations are made to help improve autoscaling.

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1.0 INTRODUCTION

The ARTIST autoscaling routines use a predicted foE to determine a range to search for the ionospheric characteristic foE. When there is no measurement of foE, the predicted foE value is reported. There are several formulations that can be used to estimate foE. In the ARTIST, the predicted foE is the CCIR model described in the CCIR Supplement Report 252-2.[1] We have also tested a foE prediction routine using a method developed by John Titheridge.[2] In this report the results of both methods are compared with the manually scaled foE for 1875 ionograms.

For determination of foF1 in ARTIST, the search range is defined at 1.2 to 1.9 times foE. In the future this range will be determined by a foF1 prediction routine. We have tested the foF1 algorithm of Millman et. al.[3] The results of the method were compared with the manually scaled foF1 values for 1,005 ionograms. A program to predict foF1 was also made available to us by L. McNamara.[4] However, it requires a file of numerical coefficients that is used by interpolation routines that are too slow and it would occupy too much memory for use in ARTIST.

In all comparisons two differences were calculated, the first is the average absolute difference AAD defined by

$$\mathrm{AAD} = \frac{\sum_{i=1}^{N} |\mathrm{Scaled} - \mathrm{Predicted}|}{N} \qquad (1)$$

and the other is simply the average difference, AD, for which cancelation of the error can occur. The AD is useful for indicating when prediction routines are continuously over or underestimating the characteristics whereas the AAD is a better indication of the quality of the routine. One should keep in mind when studying the statistics that the manual scaling using ADEP yields characteristics at a resolution of 0.1 MHz.

The prediction routines require the solar zenith angle for the location and time of day. The CCIR foE prediction uses the sunspot number, SSN, and that of Titheridge uses the 10.7 cm solar flux number, Φ. The test calculations considered the yearly mean, the monthly mean, and the daily values for SSN and Φ for each day considered. This gives an indication of the dependence of the predicted critical frequencies on these parameters.

2.0 DATA

Thirteen days of data were chosen for the initial study, twelve are from Millstone Hill, MA and the other is from Argentia, NF. The days used in the study and the number of foE and foF1 values are given in Table 1. The database covers magnetically quiet to moderately active days.

Table 1. Database of Manual Scaled Ionograms.

Station	Date	# foE values	# foF1 values
Millstone Hill Massachusetts	October 20, 1987	99	35
	February 20, 1988	123	67
	March 3, 1988	42	25
	March 4, 1988	43	29
	March 5, 1988	43	30
	March 16, 1988	106	81
	March 17, 1988	84	35
	March 23, 1988	44	29
	March 24, 1988	46	34
	March 25, 1988	46	29
	April 12, 1988	30	--
	July 13, 1988	174	121
Argentia, NF	Sept. 22, 1987	31	22

The data were manually scaled using the ADEP system and files of the scaled characteristics foE, foF1, and foF2 were produced. This produced a database of 911 foE values and 537 foF1 values to test the prediction routines.

3.0 PREDICTION ROUTINES

The ARTIST predicted foE is the recommended CCIR method described in the CCIR Supplement to report 252-2.[1] The value of foE is given by

$$foE = \left[\left(1 + 0.0094\left[\Phi_{12} - 66\right]\right) \cos^{m} \chi_{noon} \left(A + B\cos\lambda\right) D\right]^{0.25} \tag{2}$$

where Φ_{12} is the twelve month smoothed solar flux. An empirical relationship exist between the twelve month mean sunspot number, R_{12}, and the flux, Φ_{12}:

$$\Phi_{12} = 63.7 + 0.728\, R_{12} + 0.00089\, R_{12}^{2} \tag{3}$$

In equation (2) χ_{noon} is the solar zenith angle at local noon and λ is the geographic latitude (positive for north of the equator). For $|\lambda| < 32°$ the constants in equation (2) are $m = -1.93 + 1.92 \cos\lambda$; $A = 23$ and $B = 116$. And for $|\lambda| \geq 32°$ the constants are $m = 0.11 - 0.49 \cos\lambda$; $A = 92$ and $B = 35$. D is the time-of-day factor given by

(a) for $\chi' \leq 73°$

$D = \cos^{p}\chi'$, where χ' is related to the solar zenith angle χ. For $|\lambda| \leq 32°$, $\chi' = \chi$, but for $|\lambda| > 32°$ χ' is taken to be the value of χ at a time 0.05 hours earlier. For values of $|\lambda| \leq 12°$ $p = 1.31$ and for $|\lambda| > 12°$ p is given the value 1.20;

(b) for $73° < \chi' < 90°$

$D = \cos^{p} (\chi' - \delta\chi')$, where $\delta\chi' = 6.27 * 10^{-13} * (\chi' - 50)^{8}$ in degrees with $\delta\chi'$ and p is as in (a) above;

(c) for $\chi' \geq 90°$

$D = (0.077)^p \exp[-1.68\ (t1-t)]$ from midnight to dawn and
$D = (0.077)^p \exp[-1.01\ (t-t2)]$ from sunset to midnight

where t is the local time of interest in hours, t1 is the local time at dawn (χ' =90°) in hours and t2 is the local time at sunset (χ' = 90°) in hours, p has the same meaning as in (A) above. We found that the ARTIST foE prediction routine was discontinuous from (b) to (c), i.e. when χ' becomes greater than 90°.

The other foE prediction routine is taken from L. McNamara[4] and is based on the method of Titheridge[2] (J.E.T.). The formula for foE is

$$foE = 1.12 \bullet \Phi^{0.25} \bullet \cos(\chi)^{0.30} \tag{4}$$

where for $\chi > 70°$, $\cos(\chi)$ is replaced by the inverse of a Chapman function evaluated at the peak of the E layer with a scale height taken as YmE/2 and zenith angle χ.

Both methods are straight forward and require little computation time. The 12 month smoothed sunspot number and the 10.7 cm flux were taken from the National Geophysical Data Center tables.[5] The comparisons were also made using the daily and mean monthly values for SSN and Φ. This allowed us to observe the dependence of the routines on these values and to compare the quality of the routines using daily, monthly, and yearly input data. This is important since yearly, and perhaps monthly, values are the only practical values to run the algorithms, as they are used in ARTIST.

The prediction of foF1 is from the work of Millman, Bowser, and Swanson[3] (MBS) and is a slightly modified version of that by Davies.[6] The critical frequency of the F1-layer is given by

$$\mathrm{foF1} = (4.3 + 0.01\,\mathrm{SSN}) \cos^{n} (\chi_{F1}) \tag{5}$$

where χ_{F1} is the normalized F1-layer solar zenith angle given by

$$\chi_{F1} = 90° (\chi/105.5°) \qquad \text{for } 0° \le \chi \le 105.5° \tag{6}$$

The angle, 105.5°, corresponds to the zenith angle of the sun, χ (in degrees), when illuminating the F1 layer at an altitude of approximately 240 km. It is derived by assuming the absence of a screening altitude.

The exponent n, in equation (5), is solar zenith angle dependent according to reference 7

$$n = 0.2 \qquad \text{for } 0° \le \chi \le 90° \tag{7}$$

$$n = 0.2 + 0.3\,(\chi - 90°)/15.5° \qquad \text{for } 90° < \chi \le 105.5° \tag{8}$$

Equation (8) shows that, for the condition $90° < \chi \le 105.5°$. the value of n varies linearly between 0.2 and 0.5. When the calculated foF1 value at a location is greater than or equal to model foF2 values generated from numerical fits to global data, foF1 is assumed absent.

Note, the CCIR prediction routine for foE and the foF1 prediction of Millman et al. use the SSN while the foE prediction of Titheridge uses the solar 10.7 cm flux. While there is an approximate relationship between the two [see equation (3)], we have chosen to use flux values from the tables directly. Thus in the following work, the mention of the SSN will be in reference to CCIR prediction routine for foE and the foF1 prediction of Millman et al. and the mention of the flux will be in reference to the foE prediction model of Titheridge.

4.0 CALCULATIONS

Data files of the measured foE, foF1, and foF2 were created with the station location and times of the soundings. These were input to a program which, for the given times and locations, calculates the predicted values of foE and foF1. The routines use the SSN and the solar 10.7 cm flux which are available as daily, monthly, and yearly averages. Thus for each measurement three comparisons are possible, i.e. for predictions using the daily, monthly, and yearly averages for SSN and solar 10.7 cm flux. In Tables 2 and 3 comparisons of measurement with the CCIR predicted foE and the Millman et. al.[3] predicted foF1 correspond to the reported SSN and the comparisons with the Titheridge model predicted foE correspond to the reported solar 10.7 cm flux.

The difference between the measured and predicted characteristics was formed and written to additional files for statistics and plotting. In the tables and plots all times are reported in UT, the differences are reported as Measured - Predicted, and the tables report both the AAD and the AD. Table 2 gives the comparisons for the thirteen days studied. The total statistics from the 911 measured foE values and the 537 measured foF1 values are shown in Table 3.

Table 2. Measured-Predicted Frequencies in MHz, AAD and AD

	SSN	10.7 cm flux		foE CCIR	foE J.E.T.	foF1 MBS
Millstone Hill 1988 day 51 N(E) = 123 N(F1) = 67						
Daily Values	51.00	106.50	AAD	.09	.09	.28
			AD	-.06	.06	-.21
Monthly Values	40.00	102.40	AAD	.07	.10	.22
			AD	-.02	.09	-.11
Yearly Values	100.20	141.10	AAD	.25	.16	.68
			AD	-.25	-.13	-.66

Table 2. Measured-Predicted Frequencies in MHz, AAD and AD (Continued)

	SSN	10.7 cm flux		foE CCIR	foE J.E.T.	foF1 MBS
Millstone Hill 1988 day 63 N(E) = 42 N(F1) = 25						
Daily Values	72.00	99.10	AAD	.12	.14	.31
			AD	-.12	.13	-.30
Monthly Values	76.20	113.80	AAD	.14	.08	.34
			AD	-.14	.04	-.34
Yearly Values	100.20	141.10	AAD	.23	.12	.56
			AD	-.23	-.12	-.56
Millstone Hill 1988 day 64 N(E) = 43 N(F1) = 29						
Daily Values	77.00	101.90	AAD	.21	.12	.33
			AD	-.21	.05	-.33
Monthly Values	76.20	113.80	AAD	.21	.10	.33
			AD	-.21	-.02	-.32
Yearly Values	100.20	141.10	AAD	.30	.18	.54
			AD	-.30	-.18	-.54
Millstone Hill 1988 day 65 N(E) = 43 N(F1) = 30						
Daily Values	64.00	102.60	AAD	.10	.12	.25
			AD	-.10	.10	-.22
Monthly Values	76.20	113.80	AAD	.15	.08	.34
			AD	-.15	.03	-.33
Yearly Values	100.20	141.10	AAD	.24	.13	.55
			AD	-.24	-.13	-.55
Millstone Hill 1988 day 76 N(E) = 106 N(F1) = 81						
Daily Values	74.00	114.10	AAD	.19	.05	.37
			AD	-.19	-.01	-.37
Monthly Values	76.20	113.80	AAD	.20	.05	.39
			AD	-.20	-.01	-.39
Yearly Values	100.20	141.10	AAD	.29	.17	.61
			AD	-.29	-.17	-.61

Table 2. Measured-Predicted Frequencies in MHz, AAD and AD (Continued)

	SSN	10.7 cm flux		foE CCIR	foE J.E.T.	foF1 MBS
Millstone Hill 1988 day 77 N(E) = 84 N(F1) = 35						
Daily Values	99.00	117.40	AAD	.22	.07	.59
			AD	-.21	.03	-.59
Monthly Values	76.20	113.80	AAD	.14	.07	.38
			AD	-.13	.05	-.38
Yearly Values	100.20	141.10	AAD	.23	.12	.60
			AD	-.21	-.09	-.60
Millstone Hill 1988 day 83 N(E) = 44 N(F1) = 29						
Daily Values	74.00	120.90	AAD	.07	.08	.18
			AD	-.06	.07	-.12
Monthly Values	76.20	113.80	AAD	.07	.12	.18
			AD	-.07	.11	-.14
Yearly Values	100.20	141.10	AAD	.16	.06	.37
			AD	-.16	-.05	-.37
Millstone Hill 1988 day 84 N(E) = 96 N(F1) = 35						
Daily Values	83.00	123.00	AAD	.20	.25	.25
			AD	.09	.25	-.17
Monthly Values	76.20	113.80	AAD	.19	.29	.22
			AD	.10	.29	-.11
Yearly Values	100.20	141.10	AAD	.24	.23	.38
			AD	.04	.17	-.33
Millstone Hill 1988 day 85 N(E) = 46 N(F1) = 29						
Daily Values	92.00	128.50	AAD	.14	.04	.27
			AD	-.14	.02	-.27
Monthly Values	76.20	113.80	AAD	.08	.11	.15
			AD	-.08	.11	-.13
Yearly Values	100.20	141.10	AAD	.17	.07	.35
			AD	-.17	-.05	-.35

Table 2. Measured-Predicted Frequencies in MHz, AAD and AD (Continued)

	SSN	10.7 cm flux		foE CCIR	foE J.E.T.	foF1 MBS
Millstone Hill 1988 day 103† N(E) = 77						
Daily Values	118.00	130.60	AAD	.44	.38	--
			AD	.23	.35	--
Monthly Values	88.00	123.60	AAD	.41	.38	--
			AD	.29	.37	--
Yearly Values	100.20	141.10	AAD	.42	.38	--
			AD	.27	.33	--
Millstone Hill 1988 day 195 N(E) = 174 N(F1) = 121						
Daily Values	103.00	141.30	AAD	.28	.18	.55
			AD	-.06	.04	-.55
Monthly Values	112.60	157.60	AAD	.31	.22	.64
			AD	-.09	-.04	-.64
Yearly Values	100.20	141.10	AAD	.27	.18	.52
			AD	-.05	.04	-.52
Millstone Hill 1987 day 293 N(E) = 99 N(F1) = 35						
Daily Values	79.00	95.60	AAD	.25	.07	.61
			AD	-.25	.06	-.61
Monthly Values	60.60	97.40	AAD	.18	.07	.44
			AD	-.18	.05	-.44
Yearly Values	29.20	85.30	AAD	.07	.13	.19
			AD	-.05	.13	-.15
Argentia, NF 1987 day 265 N(E) = 31 N(F1) = 22						
Daily Values	23.00	81.30	AAD	.08	.17	.13
			AD	-.06	.17	-.13
Monthly Values	33.90	87.00	AAD	.12	.13	.23
			AD	-.11	.13	-.23
Yearly Values	29.20	85.30	AAD	.10	.14	.18
			AD	-.09	.14	-.18

† The major contributions for this data set are pre to sunrise foE values.

Table 3. Total Statistics for the Ionograms Studied

SSN and 10.7 cm flux		foE CCIR	foE J.E.T.	foF1 MBS
Daily Values	AAD	.18	.10	.38
	AD	-.13	.05	-.37
Monthly Values	AAD	.17	.11	.38
	AD	-.12	.04	-.35
Yearly Values	AAD	.22	.14	.50
	AD	-.17	-.05	-.50

5.0 DISCUSSION AND CONCLUSION

In Table 2, the dependence of the prediction routines on the solar indices (sun spot number or 10.7 cm solar flux) can be seen. It is important to note that the difference in the errors in the predicted characteristics one obtains from using the daily, monthly, and yearly values of the solar indices is small. These results are encouraging since from a practical standpoint the yearly or monthly values are generally used in the algorithms. It appears that no penalty urs from using the yearly mean sun spot numbers or solar fl values in the foE prediction routines.

For each day studied, plots of the measured foE and the two predicted values, the error in foE, the measured foF1 and the predicted foF1, and the error in foF1 were made. Figures 1a-1d corresponds to the first entry of Table 1, October 20, 1987 at Millstone Hill, and the figures continue in this manner to Figures 13a-13d the last entry of Table 1, September 22, 1987 at Argentia, NF. In many respects the figures provide more information about the comparison than the statistics, giving the comparison as a function of time of day.

Figures were produced using the yearly solar indices (sunspot and solar flux numbers) for the calculations. In the figures 1 through 13, those labeled **a** are plots of the measured foE, and the two predicted values. In these plots, the measured data are presented by the dots, the CCIR predicted foE values are given by the solid line, and the Titheridge routine predicted foE values are represented by the dashed line. The plots labeled **b** are the error given by foE(manual)-foE(predicted) vs. time of day. The CCIR comparisons are the solid circles and the Titheridge comparisons are the **x** symbols. The figures labeled **c** are the foF1 (measured-dots and predicted-solid line) vs. time of day. The last figure per group, labeled **d**, are the errors in the predicted foF1 values vs. time.

In comparing the results for predicting foE, on all days considered, except September 22, 1987 at Argentia, NF and October 20, 1987 at Millstone Hill, the prediction based on Titheridge's method (the dashed line) is in better agreement with the measured results. Both data sets that have CCIR results in better agreement are from 1987. This is probably a fortuitous combination of data set and the values used for the sun spot number. In general, the predictions track the measurements rather smoothly but are usually higher, but not always. The prediction routine of Titheridge appears to track the manually scaled results more closely than the CCIR prediction. The results of the statistics for the two methods indicates this as well. The averaged absolute difference, AAD, is always smaller for the Titheridge routine. More important is that the Titheridge routine is more centered on the measured values as shown by the average percent difference. The CCIR routine appears to be consistently higher than the measured results, this can be seen by comparing the AAD to the AD in Table 3. The plots of the differences (Figures labeled **b**) do not offer much insight into the prediction routines except supporting the previous conclusion, that the Titheridge predictions follow the data better than the CCIR predictions, leading to smaller errors. The observed structure in the error plots is simply due to the digital nature of the measured data. Based on the results it would appear to be wise to adopt the Titheridge prediction of foE for use in the ARTIST algorithms.

The foF1 prediction routine gave results that are generally high (see Table 3). Given the resolution of the scaling, there does not appear to be a significant penalty for using monthly or yearly mean SSN values. By comparing the AAD with the AD, one finds the foF1 prediction to be consistently higher than the measured value. This is demonstrated in the plots (set **c**). The plots also show that the foFl prediction does not track measurements as smoothly as the foE predictions. The foFl prediction may be quite useful for defining a search range for the autoscaling routines. From the foFl error plots (labeled **d**), we note that the search range defined by $foF1_{predicted}$ - 1 .MHZ to $foF1_{predicted}$ + 0.2 MHz contains all the measured values in this study.

6.0 OTHER GEOGRAPHICAL LOCATIONS

Before concluding this study, the prediction routines were tested for other geographical locations for which data were now readily available. The station locations and statistics from the study are given in Table 4. The data consist of two days where recordings were made simultaneously for five stations as shown in Table 4. In addition to this, data was also available for one month at Wallops Island, VA for which there were many F1 measurements and for one month at Kirtland Air Force Base, NM. These are shown in Table 5. The results do not change the conclusions from above, the F1 prediction routine gave slightly better statistics.

Adding the results from these other locations to the database of section 4 brings the total number of foE predictions studied to 1875 and the total number of F1 predictions considered to 1005. In Table 6, the total statistics for all of the ionograms considered are reported. For the additional data, the daily values of the sunspot number and the 10.7 cm flux were not tested. Thus, the table compares the monthly and yearly values. Again these results support the conclusions of section 5, i.e. that there is no significant penalty for using yearly or monthly mean SSN and 10.7 cm flux values. and the Titheridge foE prediction gives better agreement than the CCIR method.

Table 4. Statistics for Days 282 and 284, 1989 for Five Stations, Yearly SSN (158.9) and 10.7 cm Flux (212.5).

		foE CCIR	foE J.E.T	foF1 MBS
Argentia, NF 1989,	N(E) = 130		N(F1) = 7	
AAD		.10	.11	.69
AD		-.04	-.02	.28
Goosebay, Labrador	N(E) = 78		N(F1) = 0	
AAD		.09	.10	
AD		-.08	-.05	
Bermuda, FL	N(E) = 46		N(F1) = 1	
AAD		.06	.09	.03
AD		.00	.03	-.03
Millstone, MA	N(E) = 79		N(F1) = 1	
AAD		.06	.07	.61
AD		-.02	-.00	-.61
Wallops Island, VA	N(E) = 35		N(F1) = 0	
AAD		.07	.07	
AD		-.03	-.03	

Table 5. Statistics for Two Months at other Geographic Locations, Yearly SSN and 10.7 cm Flux.

SSN	10.7 cm flux		foE CCIR	foE J.E.T	foF1 MBS
Wallops Island, VA		N(E) = 553		N(F1) = 459	
July, 1988					
100.20	141.10	AAD	.15	.10	.27
		AD	-.11	.01	-.24
Kirtland AFB, NM		N(E) = 43		N(F1) = 0	
January, 1990					
158.90	212.50	AAD	.12	.12	
		AD	.04	.04	

Table 6. Total Statistics for the Ionograms Studied.

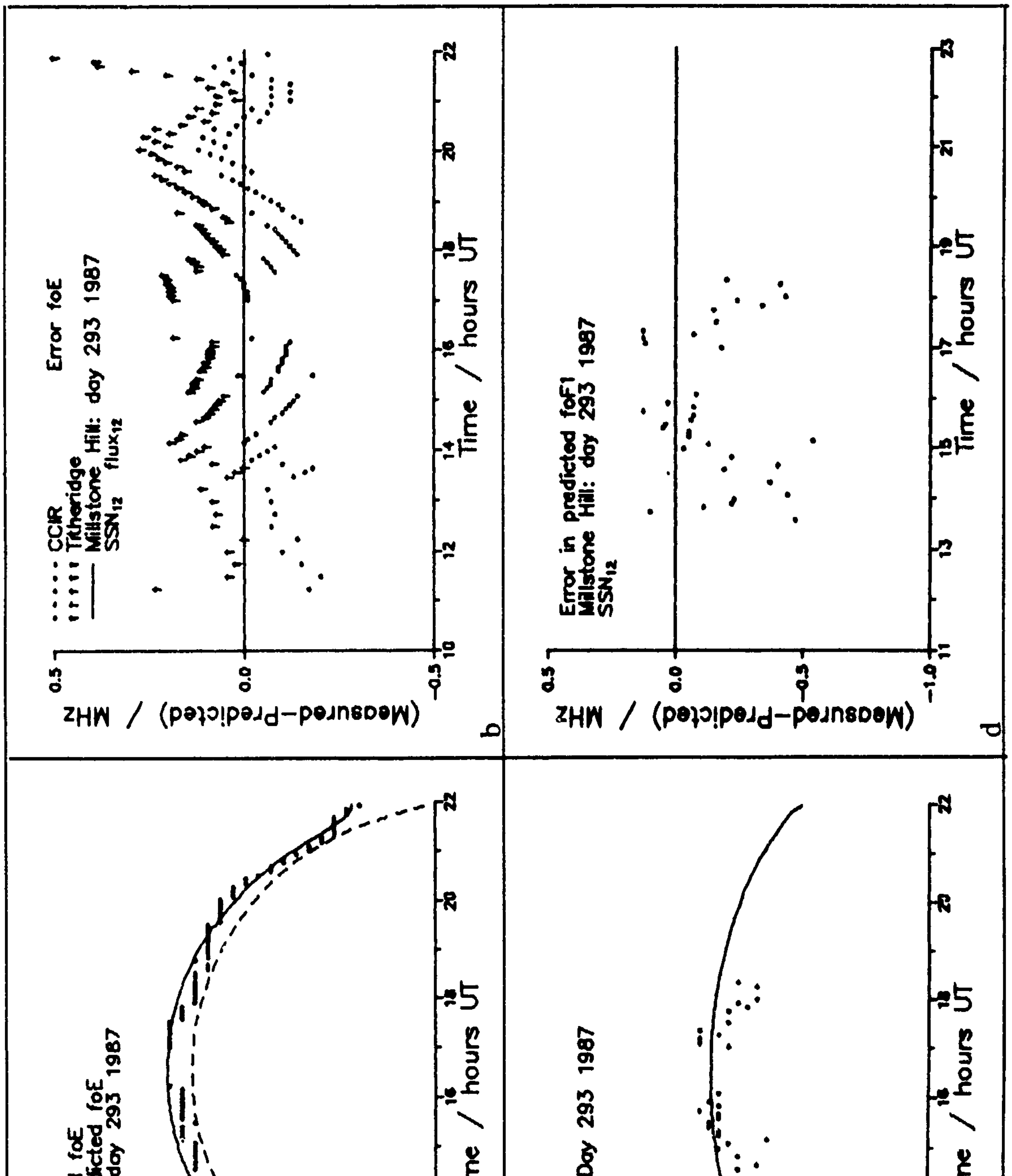
Solar Indices		foE CCIR	foE J.E.T.	foF1 MBS
		N(E) = 1875		N(F1) = 1005
Monthly Values	AAD	.17	.11	.38
	AD	-.13	.00	-.36
Yearly Values	AAD	.17	.12	.40
	AD	-.12	-.02	-.37

Figure 1a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for October 20, 1987, Millstone Hill, MA.

Figure 1b. Error foE(manual)-foE(predicted) vs. time of day for October 20, 1987, Millstone Hill, MA.

Figure 1c. foF1 (measured and predicted) vs. time of day for October 20, 1987, Millstone Hill, MA.

Figure 1d. Error foF1(manual)-foF1(predicted) vs. time of day for October 20, 1987, Millstone Hill, MA.



Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 293 1987
SSN12 flux12
foE / MHz
Time / hours UT
a
CCIR
Titheridge
Millstone Hill: day 293 1987
SSN12 flux12
Error foE
(Measured−Predicted) / MHz
Time / hours UT
b
Measured foF1
Predicted foF1
Millstone Hill: Day 293 1987
SSN12 flux12
foF1 / MHz
Time / hours UT
c
Error in predicted foF1
Millstone Hill: day 293 1987
SSN12
(Measured−Predicted) / MHz
Time / hours UT
d

Figure 2a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for February 20, 1988, Millstone Hill, MA.

Figure 2b. Error foE(manual)-foE(predicted) vs. time of day for February 20, 1988, Millstone Hill, MA.

Figure 2c. foF1 (measured and predicted) vs. time of day for February 20, 1988, Millstone Hill, MA.

Figure 2d. Error foF1(manual)-foF1(predicted) vs. time of day for February 20, 1988, Millstone Hill, MA.

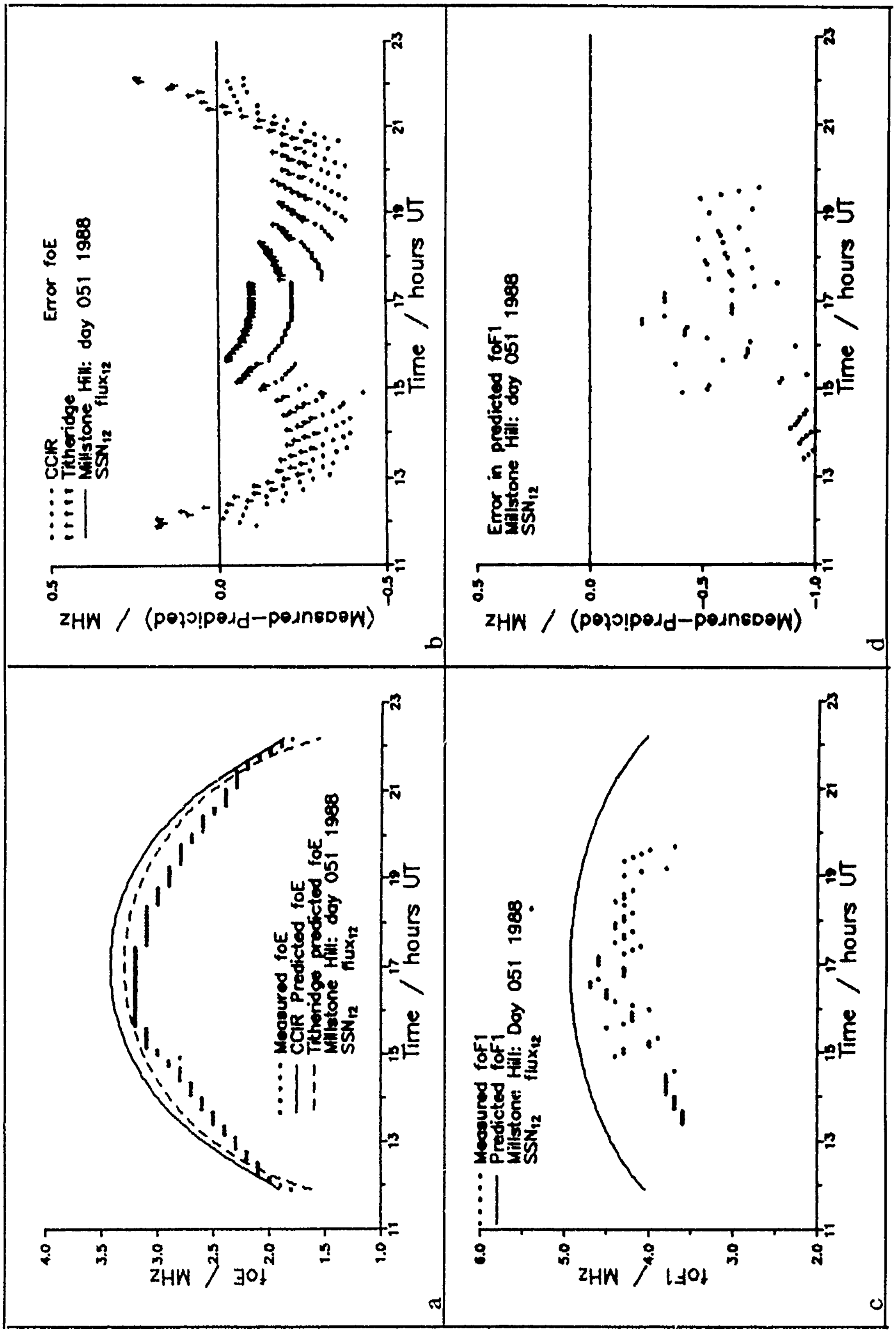

a
foE / MHz
Time / hours UT
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 051 1988
SSN12 flux12
b
(Measured−Predicted) / MHz
CCIR
Titheridge
Millstone Hill: day 051 1988
SSN12 flux12
Error foE
c
foF1 / MHz
Measured foF1
Predicted foF1
Millstone Hill: Day 051 1988
SSN12 flux12
d
Error in predicted foF1
Millstone Hill: day 051 1988
SSN12

Figure 3a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 3, 1988, Millstone Hill, MA.

Figure 3b. Error foE(manual)-foE(predicted) vs. time of day for March 3, 1988, Millstone Hill, MA.

Figure 3c. foF1 (measured and predicted) vs. time of day for March 3, 1988, Millstone Hill, MA.

Figure 3d. Error foF1(manual)-foF1(predicted) vs. time of day for March 3, 1988, Millstone Hill, MA.

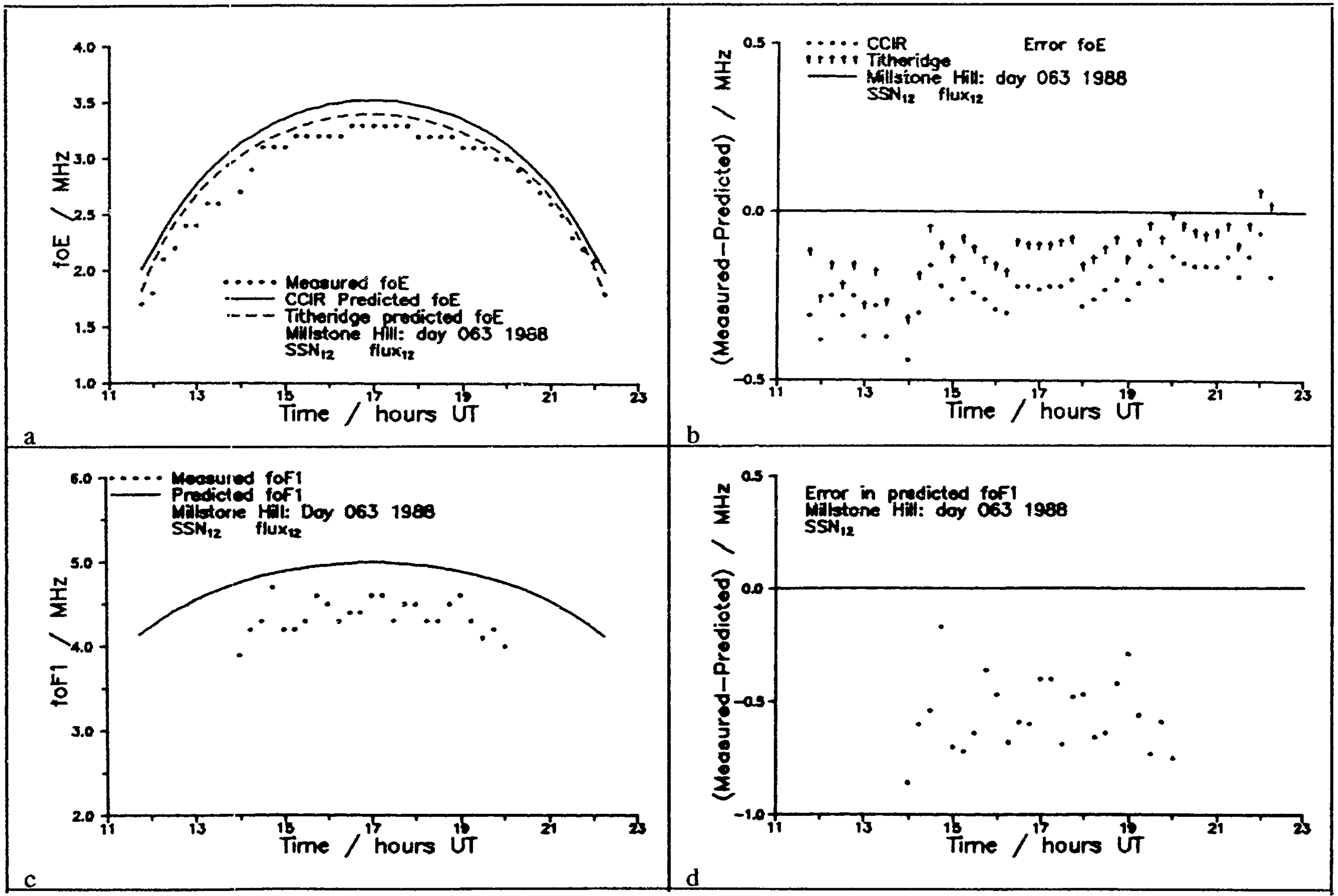

foE / MHz
Time / hours UT
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 063 1988
SSN12 flux12
a
(Measured−Predicted) / MHz
CCIR
Titheridge
Error foE
Millstone Hill: day 063 1988
SSN12 flux12
b
foF1 / MHz
Measured foF1
Predicted foF1
Millstone Hill: Day 063 1988
SSN12 flux12
c
Error in predicted foF1
Millstone Hill: day 063 1988
SSN12
d

Figure 4a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 4, 1988, Millstone Hill, MA.

Figure 4b. Error foE(manual)-foE(predicted) vs. time of day for March 4, 1988, Millstone Hill, MA.

Figure 4c. foF1 (measured and predicted) vs. time of day for March 4, 1988, Millstone Hill, MA.

Figure 4d. Error foF1(manual)-foF1(predicted) vs. time of day for March 4, 1988, Millstone Hill, MA.

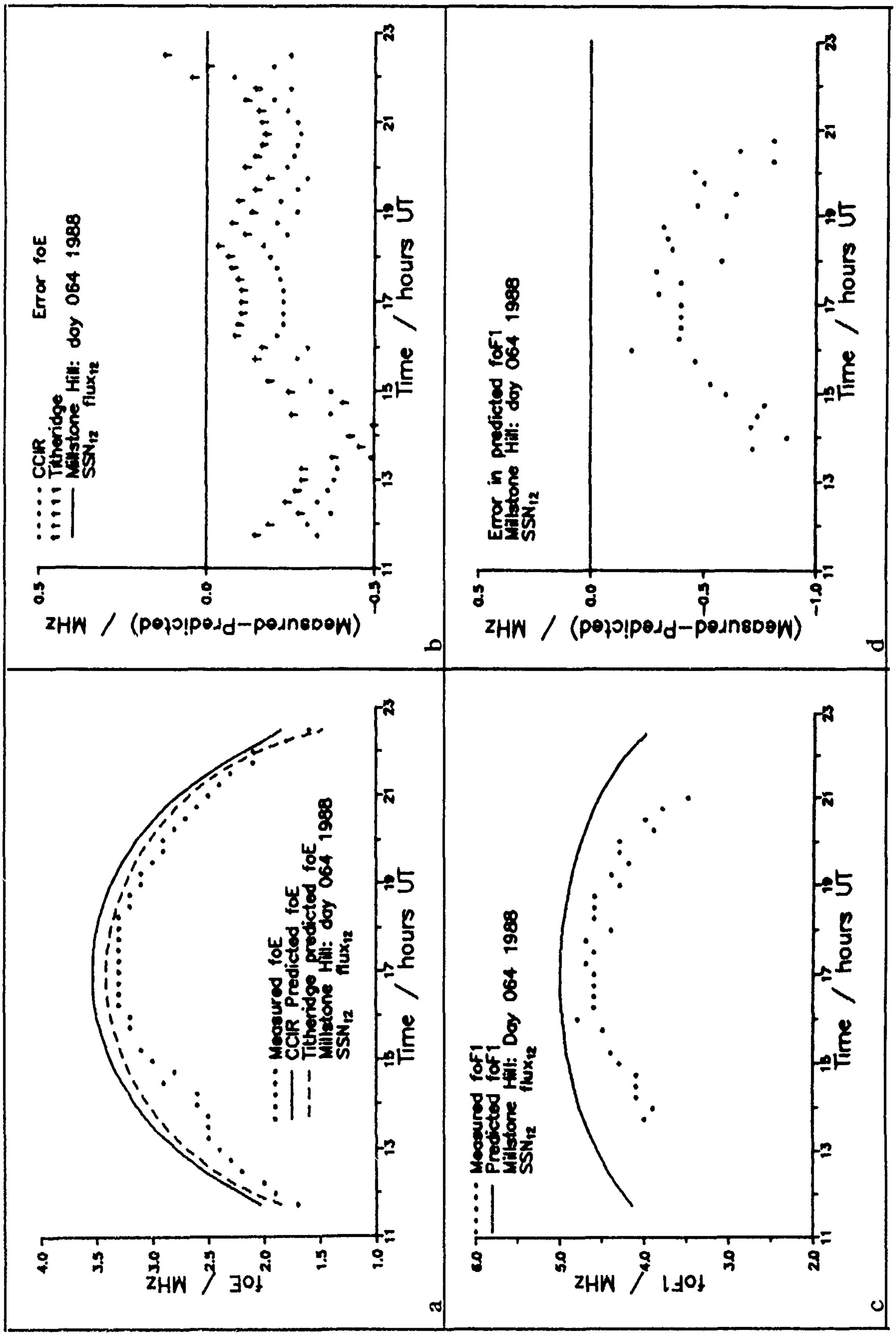
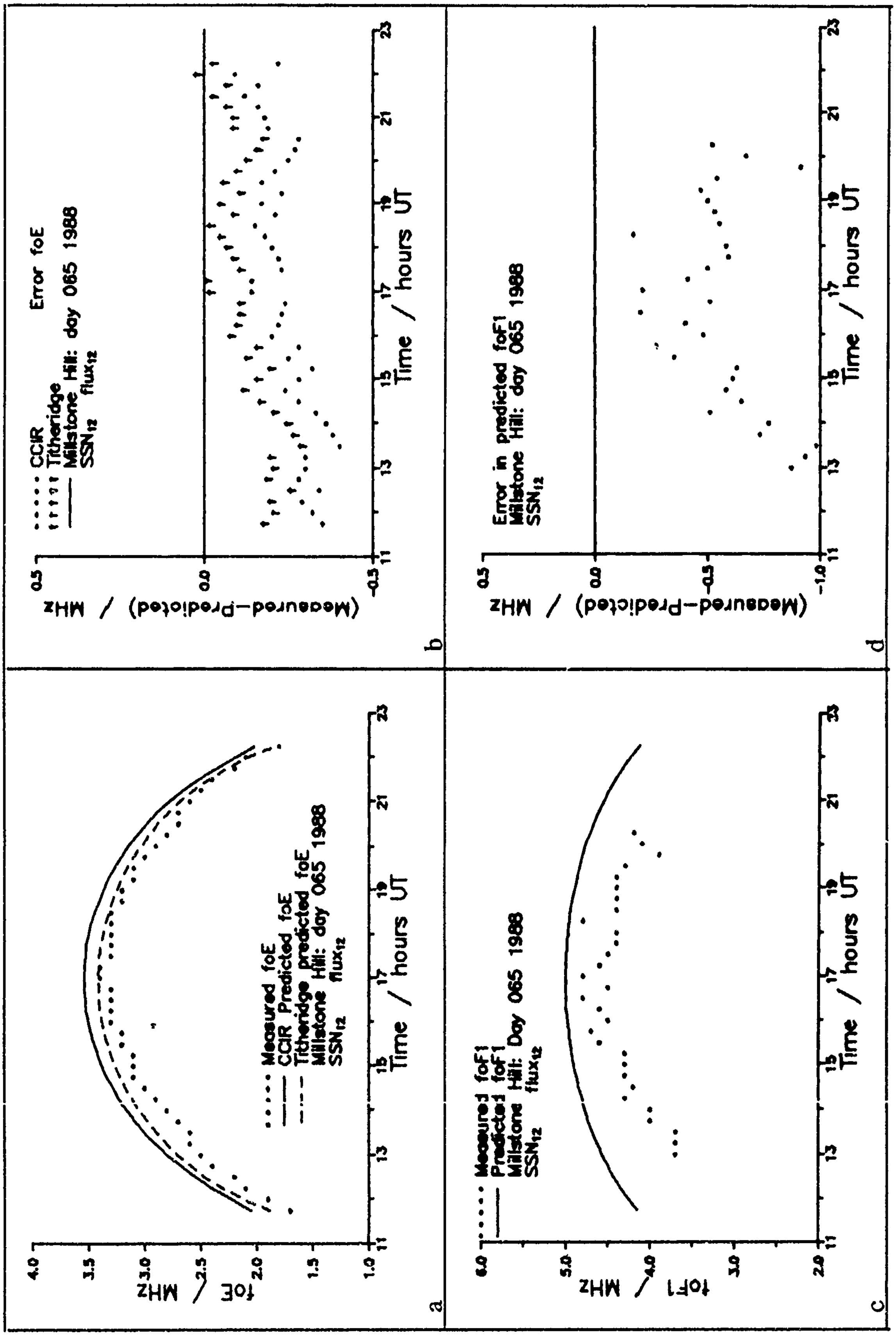

Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 064 1988
SSN12 flux12
foE / MHz
Time / hours UT
a
CCIR
Titheridge
Millstone Hill: day 064 1988
SSN12 flux12
Error foE
(Measured-Predicted) / MHz
Time / hours UT
b
Measured foF1
Predicted foF1
Millstone Hill: Day 064 1988
SSN12 flux12
foF1 / MHz
Time / hours UT
c
Error in predicted foF1
Millstone Hill: day 064 1988
SSN12
(Measured-Predicted) / MHz
Time / hours UT
d

Figure 5a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 5, 1988, Millstone Hill, MA.

Figure 5b. Error foE(manual)-foE(predicted) vs. time of day for March 5, 1988, Millstone Hill, MA.

Figure 5c. foF1 (measured and predicted) vs. time of day for March 5, 1988, Millstone Hill, MA.

Figure 5d. Error foF1(manual)-foF1(predicted) vs. time of day for March 5, 1988, Millstone Hill, MA.



Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 065 1988
SSN_{12} $flux_{12}$
foE / MHz
Time / hours UT
a
CCIR
Titheridge
Millstone Hill: day 065 1988
SSN_{12} $flux_{12}$
Error foE
(Measured−Predicted) / MHz
Time / hours UT
b
Measured foF1
Predicted foF1
Millstone Hill: Day 065 1988
SSN_{12} $flux_{12}$
foF1 / MHz
Time / hours UT
c
Error in predicted foF1
Millstone Hill: day 065 1988
SSN_{12}
(Measured−Predicted) / MHz
Time / hours UT
d

Figure 6a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 16,1988, Millstone Hill, MA.

Figure 6b. Error foE(manual)-foE(predicted) vs. time of day for March 16,1988, Millstone Hill, MA.

Figure 6c. foF1 (measured and predicted) vs. time of day for March 16,1988, Millstone Hill, MA.

Figure 6d. Error foF1(manual)-foF1(predicted) vs. time of day for March 16,1988, Millstone Hill, MA.

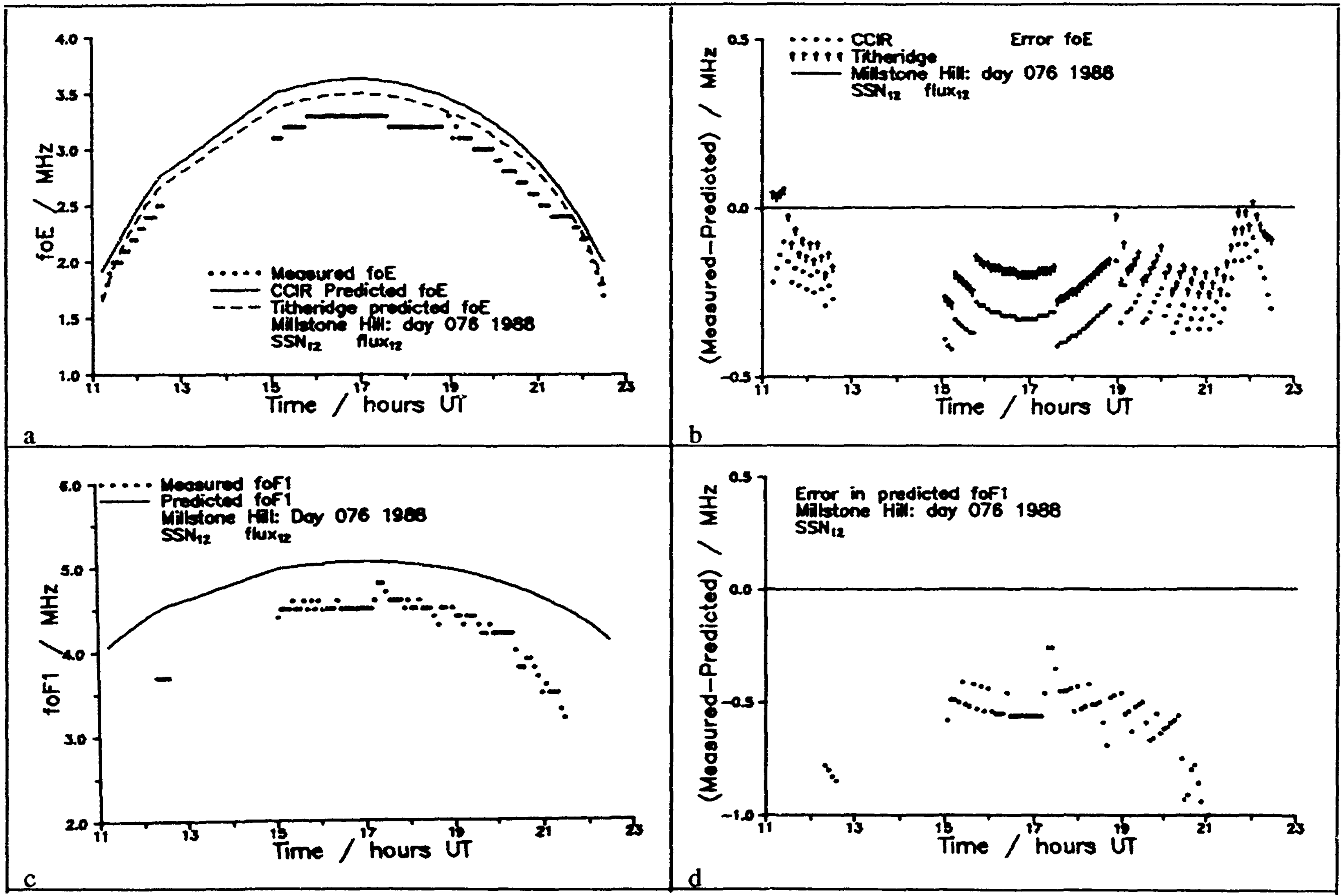

a
foE / MHz
Time / hours UT
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 076 1988
SSN12 flux12
b
(Measured−Predicted) / MHz
CCIR
Titheridge
Millstone Hill: day 076 1988
SSN12 flux12
Error foE
c
foF1 / MHz
Measured foF1
Predicted foF1
Millstone Hill: Day 076 1988
SSN12 flux12
d
Error in predicted foF1
Millstone Hill: day 076 1988
SSN12

Figure 7a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 17, 1988, Millstone Hill, MA.

Figure 7b. Error foE(manual)-foE(predicted) vs. time of day for March 17, 1988, Millstone Hill, MA.

Figure 7c. foF1 (measured and predicted) vs. time of day for March 17, 1988, Millstone Hill, MA.

Figure 7d. Error foF1(manual)-foF1(predicted) vs. time of day for March 17, 1988, Millstone Hill, MA.

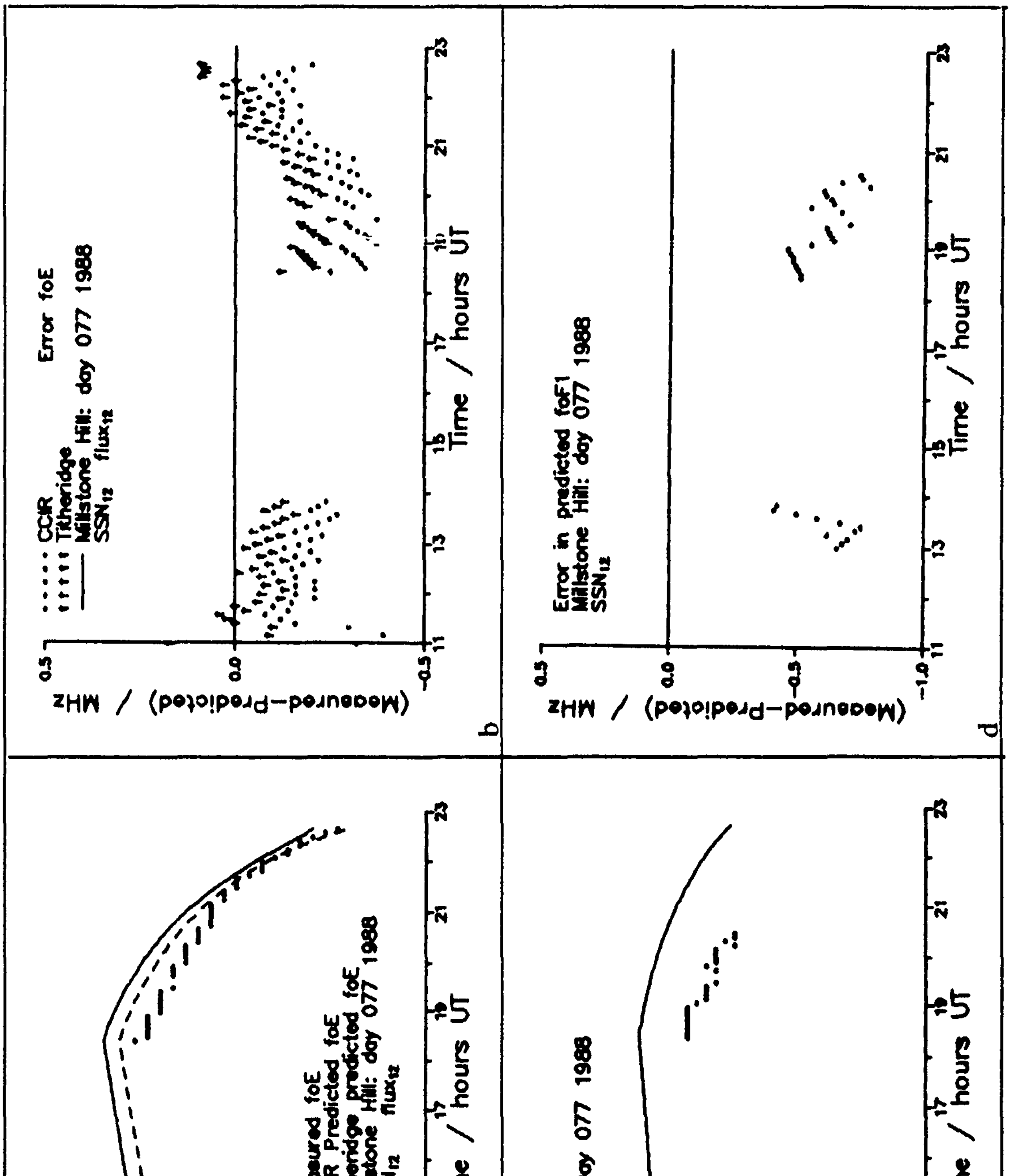

foE / MHz
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 077 1988
SSN12 flux12
Time / hours UT
a
(Measured–Predicted) / MHz
CCIR
Titheridge
Millstone Hill: day 077 1988
SSN12 flux12
Error foE
Time / hours UT
b
foF1 / MHz
Measured foF1
Predicted foF1
Millstone Hill: Day 077 1988
SSN12 flux12
Time / hours UT
c
(Measured–Predicted) / MHz
Error in predicted foF1
Millstone Hill: day 077 1988
SSN12
Time / hours UT
d

Figure 8a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 23, 1988, Millstone Hill, MA.

Figure 8b. Error foE(manual)-foE(predicted) vs. time of day for March 23, 1988, Millstone Hill, MA.

Figure 8c. foF1 (measured and predicted) vs. time of day for March 23, 1988, Millstone Hill, MA.

Figure 8d. Error foF1(manual)-foF1(predicted) vs. time of day for March 23, 1988, Millstone Hill, MA.

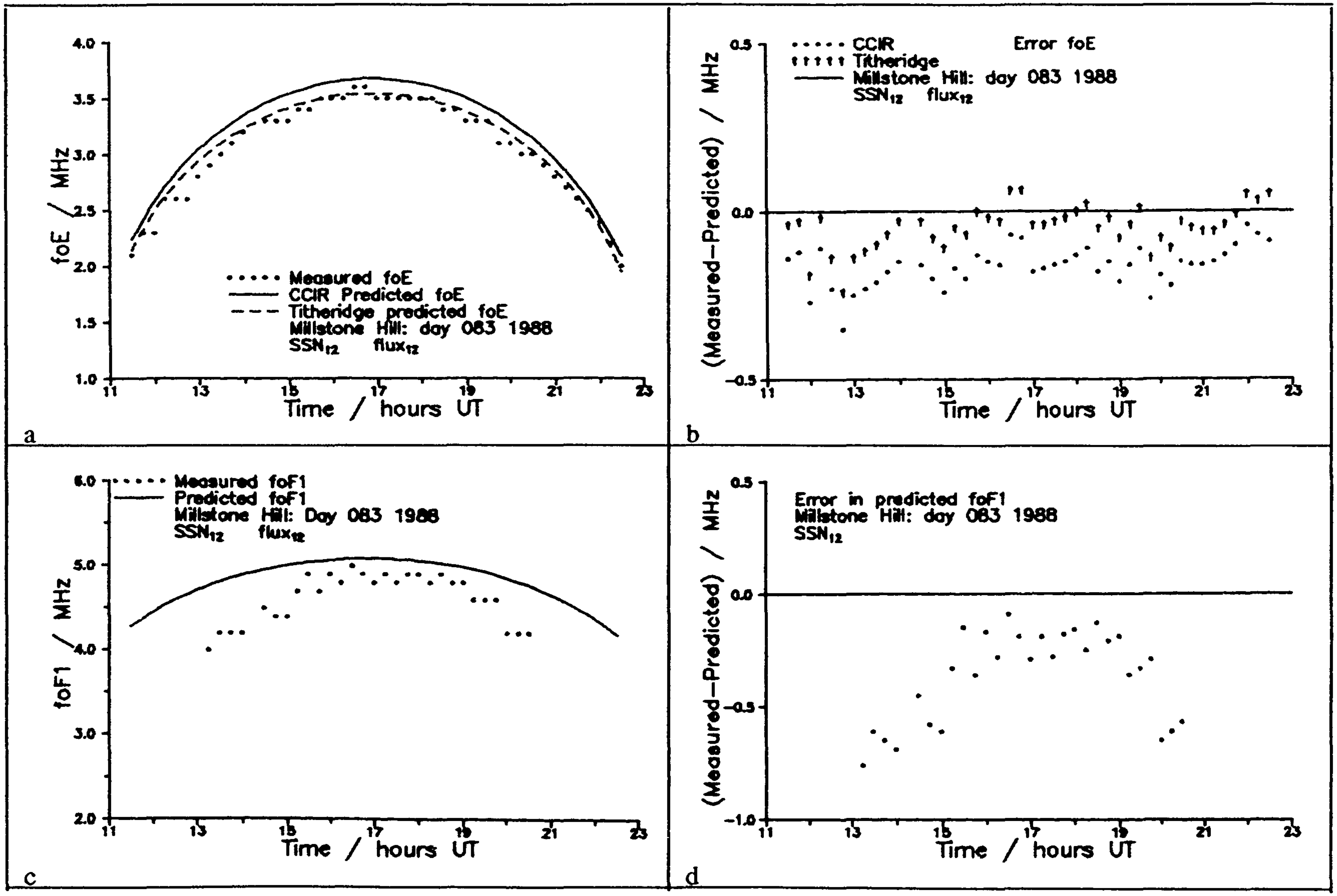
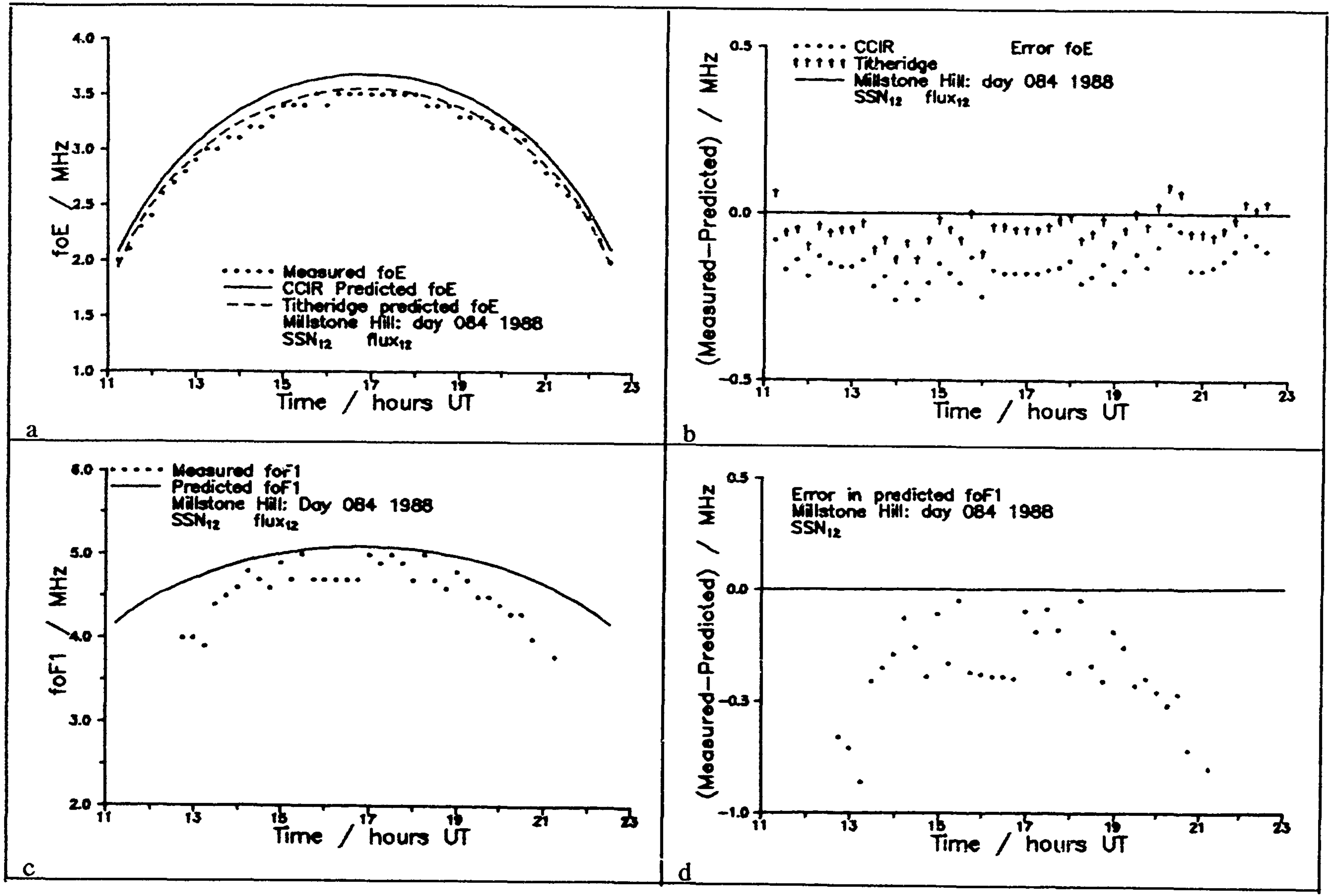

Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 083 1988
SSN12 flux12
foE / MHz
Time / hours UT
a
CCIR
Titheridge
Millstone Hill: day 083 1988
SSN12 flux12
Error foE
(Measured-Predicted) / MHz
Time / hours UT
b
Measured foF1
Predicted foF1
Millstone Hill: Day 083 1988
SSN12 flux12
foF1 / MHz
Time / hours UT
c
Error in predicted foF1
Millstone Hill: day 083 1988
SSN12
(Measured-Predicted) / MHz
Time / hours UT
d

Figure 9a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 24, 1988, Millstone Hill, MA.

Figure 9b. Error foE(manual)-foE(predicted) vs. time of day for March 24, 1988, Millstone Hill, MA.

Figure 9c. foF1 (measured and predicted) vs. time of day for March 24, 1988, Millstone Hill, MA.

Figure 9d. Error foF1(manual)-foF1(predicted) vs. time of day for March 24, 1988, Millstone Hill, MA.



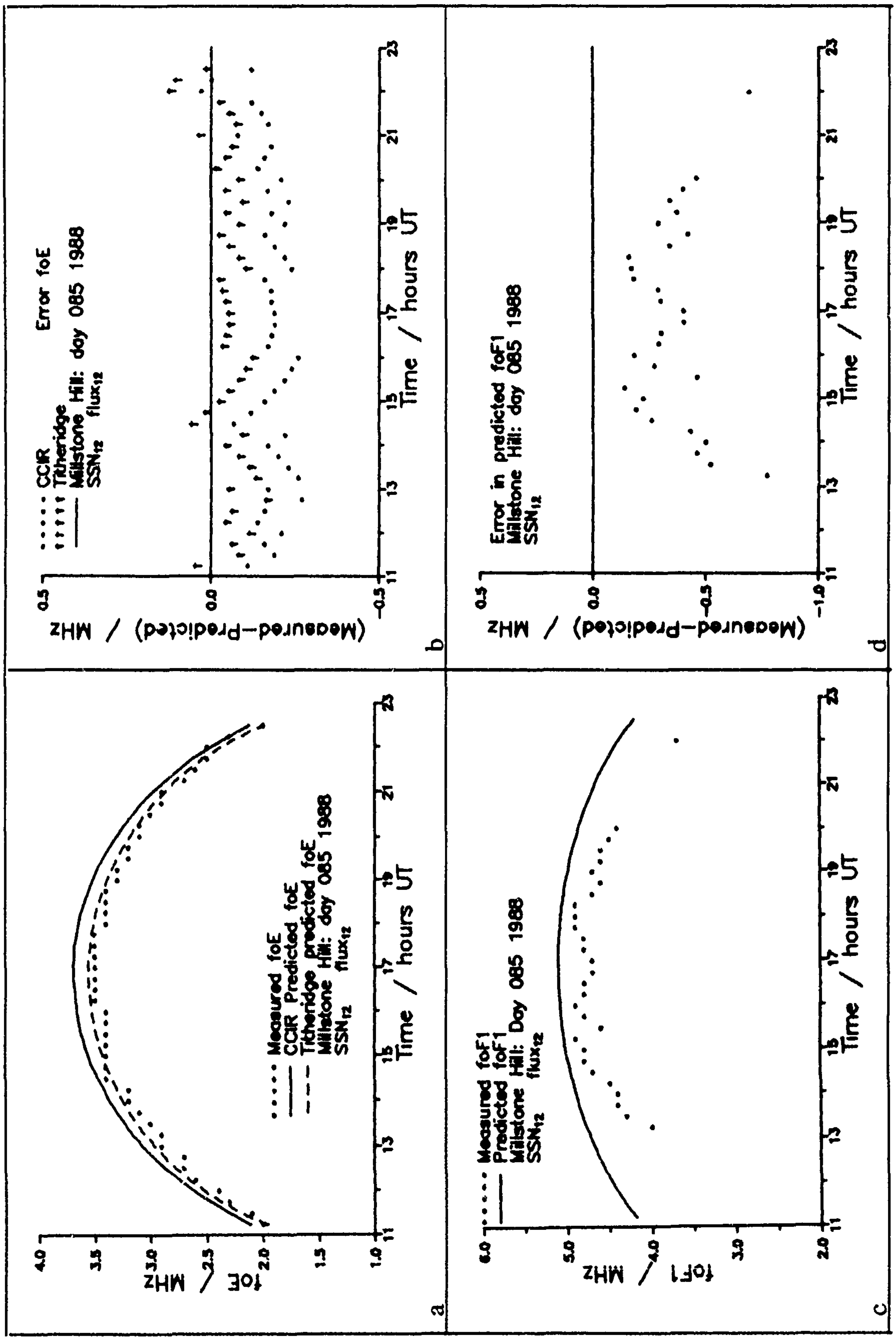
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 084 1988
SSN12 flux12
foE / MHz
Time / hours UT
a
CCIR
Titheridge
Error foE
Millstone Hill: day 084 1988
SSN12 flux12
(Measured−Predicted) / MHz
Time / hours UT
b
Measured foF1
Predicted foF1
Millstone Hill: Day 084 1988
SSN12 flux12
foF1 / MHz
Time / hours UT
c
Error in predicted foF1
Millstone Hill: day 084 1988
SSN12
(Measured−Predicted) / MHz
Time / hours UT
d

Figure 10a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for March 25, 1988, Millstone Hill, MA.

Figure 10b. Error foE(manual)-foE(predicted) vs. time of day for March 25, 1988, Millstone Hill, MA.

Figure 10c. foF1 (measured and predicted) vs. time of day for March 25, 1988, Millstone Hill, MA.

Figure 10d. Error foF1(manual)-foF1(predicted) vs. time of day for March 25, 1988, Millstone Hill, MA.



a
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 085 1988
SSN12 flux12
foE / MHz
Time / hours UT
b
CCIR
Titheridge
Millstone Hill: day 085 1988
SSN12 flux12
Error foE
(Measured−Predicted) / MHz
Time / hours UT
c
Measured foF1
Predicted foF1
Millstone Hill: Day 085 1988
SSN12 flux12
foF1 / MHz
Time / hours UT
d
Error in predicted foF1
Millstone Hill: day 085 1988
SSN12
(Measured−Predicted) / MHz
Time / hours UT

Figure 11a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for April 12, 1988, Millstone Hill, MA.

Figure 11b. Error foE(manual)-foE(predicted) vs. time of day for April 12, 1988, Millstone Hill, MA.

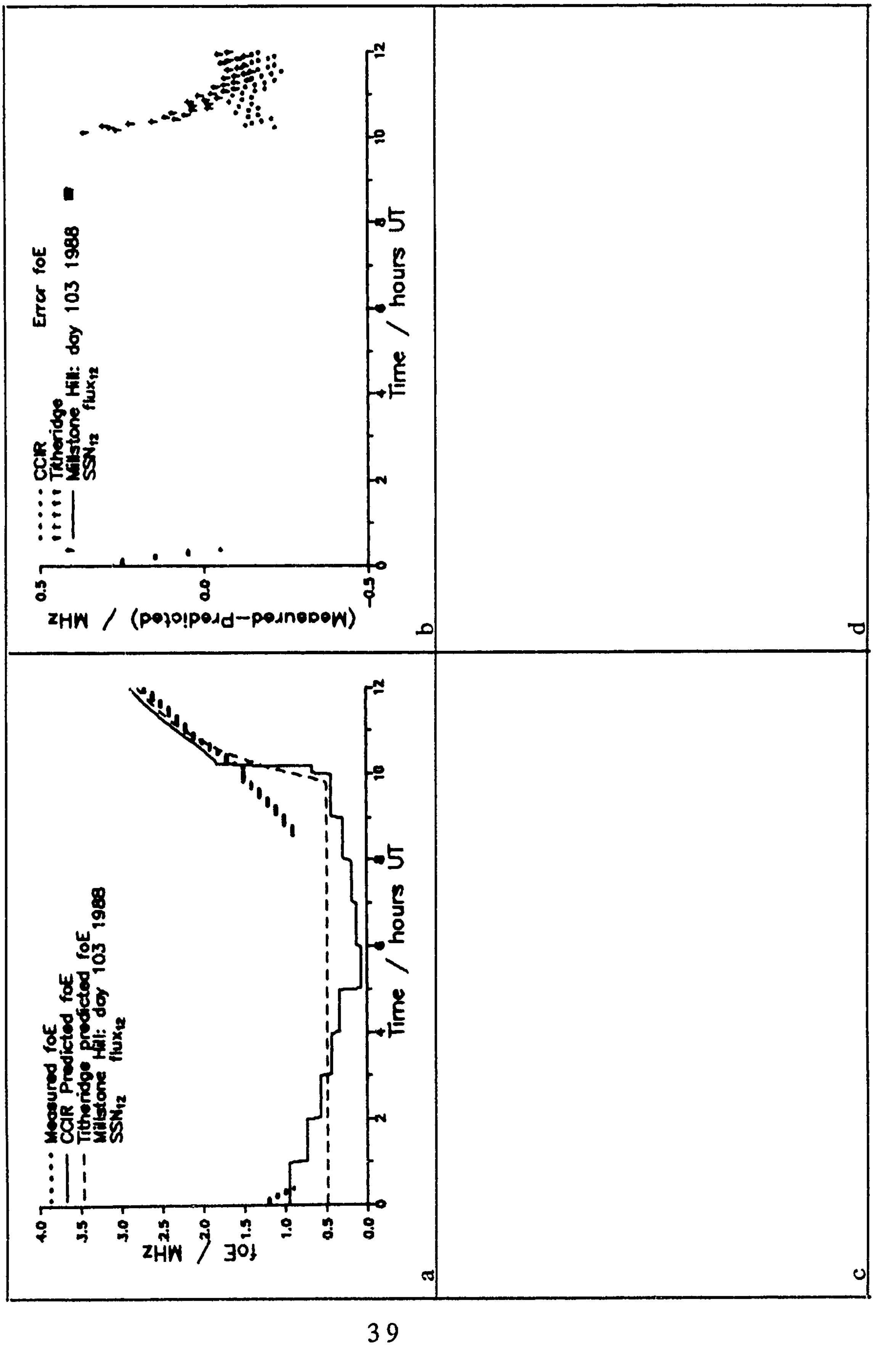
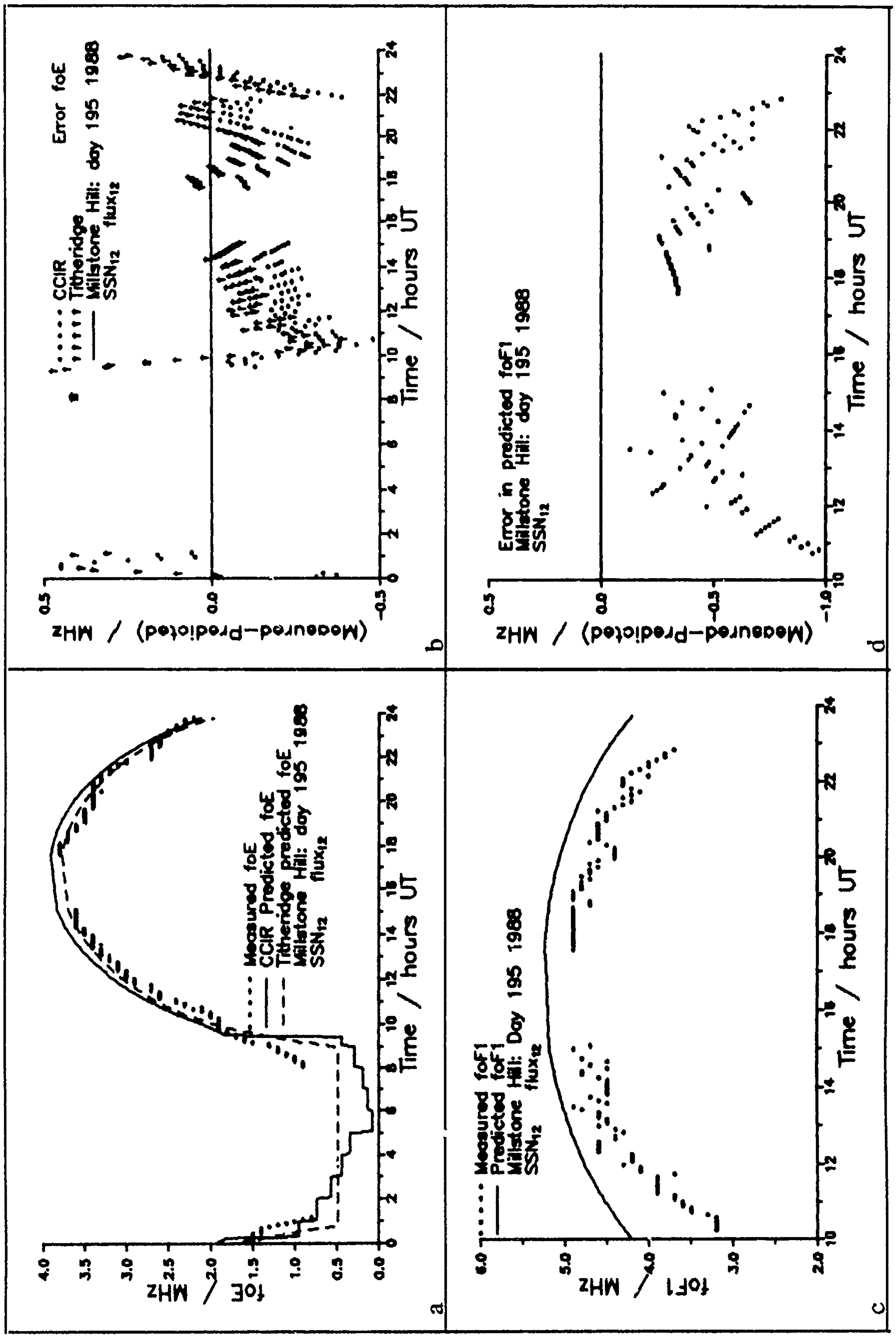

Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 103 1988
SSN12 flux12
foE / MHz
Time / hours UT
a
Error foE
CCIR
Titheridge
Millstone Hill: day 103 1988
SSN12 flux12
(Measured−Predicted) / MHz
Time / hours UT
b
c
d

Figure 12a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for July 13, 1988, Millstone Hill, MA.

Figure 12b. Error foE(manual)-foE(predicted) vs. time of day for July 13, 1988, Millstone Hill, MA.

Figure 12c. foF1 (measured and predicted) vs. time of day for July 13, 1988, Millstone Hill, MA.

Figure 12d. Error foF1(manual)-foF1(predicted) vs. time of day for July 13, 1988, Millstone Hill, MA.



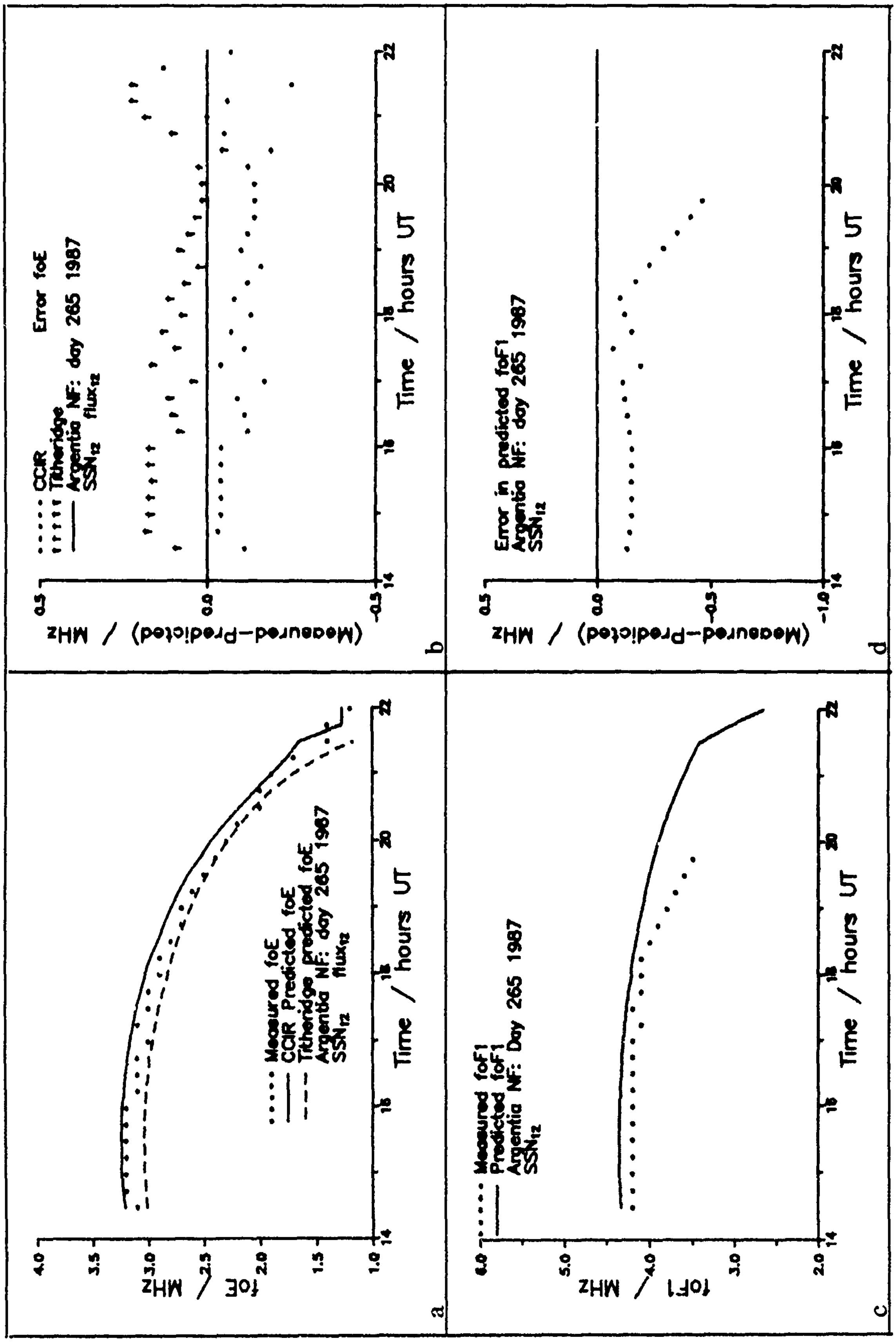
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Millstone Hill: day 195 1988
SSN$_{12}$ flux$_{12}$
foE / MHz
Time / hours UT
a
CCIR
Titheridge
Millstone Hill: day 195 1988
SSN$_{12}$ flux$_{12}$
Error foE
(Measured−Predicted) / MHz
Time / hours UT
b
Measured foF1
Predicted foF1
Millstone Hill: Day 195 1988
SSN$_{12}$ flux$_{12}$
foF1 / MHz
Time / hours UT
c
Error in predicted foF1
Millstone Hill: day 195 1988
SSN$_{12}$
(Measured−Predicted) / MHz
Time / hours UT
d

Figure 13a. foE (measured, CCIR predicted, and Titheridge predicted) vs. time of day for September 22, 1987, Argentia, NF.

Figure 13b. Error foE(manual)-foE(predicted) vs. time of day for September 22, 1987, Argentia, NF.

Figure 13c. foF1 (measured and predicted) vs. time of day for September 22, 1987, Argentia, NF.

Figure 13d. Error foF1(manual)-foF1(predicted) vs. time of day for September 22, 1987, Argentia, NF.


a
Measured foE
CCIR Predicted foE
Titheridge predicted foE
Argentia NF: day 265 1987
SSN_{12} $flux_{12}$
foE / MHz
Time / hours UT
b
Error foE
CCIR
Titheridge
Argentia NF: day 265 1987
SSN_{12} $flux_{12}$
(Measured−Predicted) / MHz
Time / hours UT
c
Measured foF1
Predicted foF1
Argentia NF: Day 265 1987
SSN_{12}
foF1 / MHz
Time / hours UT
d
Error in predicted foF1
Argentia NF: day 265 1987
SSN_{12}
(Measured−Predicted) / MHz
Time / hours UT

7.0 REFERENCES

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3. G. H. Millman, C. A. Bowser, and R. W. Swanson, "An Ionospheric Model for HF Sky-Wave Backscatter Radar," AGARD Conference Proceedings No. 441, Paper 43, Munich, FRG, 1988.

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